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Small plastic debris changes water movement and heat transfer through beach sediments

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ABSTRACT

We investigated the physical properties of beaches contaminated with plastic fragments. We compared sediment cores from Hawai'i Island's Kamilo Beach, notable for plastic accumulation, to cores from a nearby beach. Compared to the nearby beach, Kamilo sediments contained more plastics (up to 30.2% by weight), were coarser-grained, and were more permeable (t-test, $p < 0.0001$). 85% of the fragments were polyethylene, and 95% were concentrated in the top 15 cm of the cores. We constructed artificial cores of standardized grain size and varying plastic-to-sediment ratios. Adding plastic significantly increased the permeability (ANOVA, $p = 0.002$), which was partially attributed to the fragments increasing the mean grain size. Sediments with plastic warmed more slowly (16% maximum decrease in thermal diffusivity), and reached lower maximum temperatures (21% maximum increase in heat capacity). These changes have a variety of potential effects on beach organisms, including those with temperature-dependent sex-determination such as sea turtle eggs.

1. Introduction

Although synthetic polymers have made incalculable contributions to the quality of human life in the past century, their longevity presents a challenge when disposed improperly. Many forms of plastic have been accumulating in global environments for decades (Barnes et al., 2009), and may be continuing to increase in concentration in marine environments (Thompson et al., 2004). Impacts of the plastic material on the ocean include entanglement in, smothering by, or ingestion of plastics by a variety of taxa; concentration, transport and release of harmful chemicals; and facilitation of invasion via rafting (reviewed in Gregory, 2009). Larger plastic items readily fragment in beach environments, and these fragments have been incorporated in coastal sediments around the world (Barnes et al., 2009). These fragments may remain on beaches longer than larger items because coastal cleanup operations seldom remove them due to the extraordinary effort that would be needed to do so. Possible impacts on nearshore environments from small plastic debris, whether pre-production pellets or fragments of larger items, include ingestion by a variety of organisms (Graham and Thompson, 2009; Laist, 1997) or sediment contamination from leached plasticizers (Oehlmann et al., 2009) or adsorbed persistent organic pollutants (Mato et al., 2001; Rios et al., 2007). Here we suggest a novel potential impact, the alteration of the physical properties of beaches due to the inclusion of small plastic debris in beach sediment. We assess the depth of plastic fragments mixed into beach sediments, determine potential changes to water movement and heat transfer due to these fragments, and speculate on how these changes affect beach-dwelling organisms.

2. Site description and methods

A large amount of marine debris enters the nearshore environments of the Hawaiian Archipelago (Cooper and Corcoran, 2010; Dameron et al., 2007; McDermid and McMullen, 2004), most likely due to its proximity to the North Pacific Subtropical Convergent Zone where marine debris accumulates (Kubota, 1993; Pichel et al., 2007). Kamilo Beach, on the southern portion of the island of Hawai'i (Fig. 1), is notable for debris accumulation dating back to ancient times due to convergent currents in the area (Ebbesmeyer and Scigliano, 2009). This so-called "Junk Beach" has been the subject of documentaries, and perhaps one of the most labor-intensive clean-up operations of plastic debris ever. Currently, the Hawai'i Wildlife Fund organizes clean-ups at the beach or nearby coastline four times a year (approximately once every three months) to keep up with the accumulation rates. Although this group performs some removal of small plastic fragments (here we define "small" as <10 mm maximum dimension), it is mainly for demonstration purposes, and would be prohibitively expensive and time-consuming to do for the entire ~0.5 km length of the beach. Therefore, Kamilo Beach represents an unintended experiment on the effects of large volumes of small plastic fragments on beach environments.

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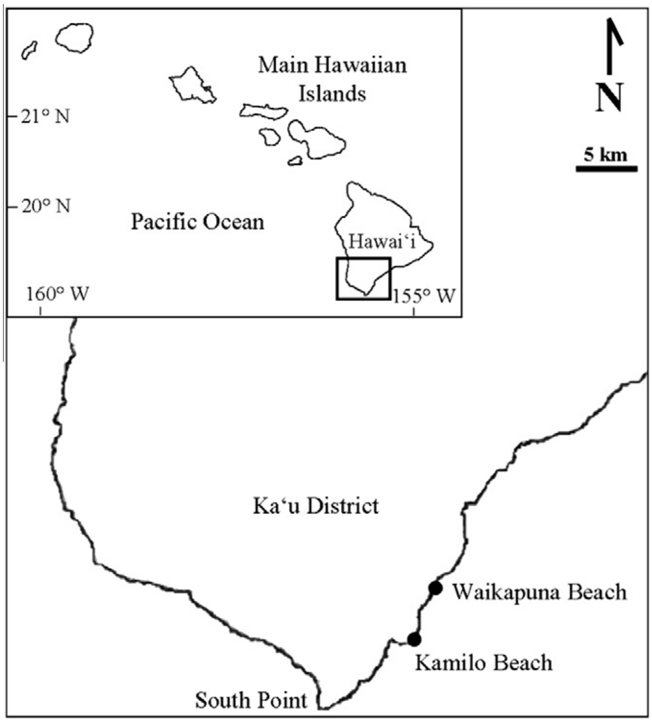

Fig. 1. Map of the study area on the southern portion of Hawai'i Island in the north central Pacific Ocean.

We collected five sets of three, 5-cm-diameter sediment cores from randomly placed transects perpendicular to the shoreline on Kamilo Beach (18°58′26″N, 155°35′58″W) in September 2010. Each transect consisted of one core taken at the center of the prominent wrack line, the second core taken one meter seaward, and a third core taken two meters landward from the wrack line (on the "berm"). The total beach width at each transect averaged 12.02 m. The transect lines were oriented to the northeast from 40° to 80° along the curvature of the beach, and the beach face slope averaged 0.149. Cores were taken approximately four months after the previous beach cleanup operation (although such operations do not remove significant amounts of small plastic fragments). Lithogenous sediments at Kamilo were a mix of dark, basaltic sediments and white, calcium carbonate sediments, a so-called "salt and pepper" beach.

For comparison purposes, a "control" beach, Waikapuna, was chosen because it is within close proximity to Kamilo Beach (Fig. 1), appeared to have similar sediment characteristics, but does not apparently accumulate large amounts of plastic debris. Waikapuna (19°01′12″N, 155°34′46″W) is located approximately 6 km northeast of Kamilo, and is a shorter (120 m) and wider (mean 24.72 m) beach. Five randomly-selected transects and 15 cores were taken as at Kamilo. The orientation of the transects on the more curved beach ranged from nearly north (20°) to southeast (140°). The mean slope of the beach face was 0.139. No beach clean-ups have been organized on Waikapuna, although some plastic debris was noted.

Permeability, the ability of beach sediments to transmit fluids, was measured on the intact cores before they were divided into 5 cm sections to measure porosity, percent plastic, and grain size. Permeability (K) of all 30 cores was estimated by making three replicate measurements of each core by timing the passage of standardized volumes of tap water at a "constant head" (Fetter, 2001). Cores were collected and tested in clear polyvinyl chloride (PVC) tubes of 5 cm interior diameter. In the lab, the bottom cap was replaced with a 2 mm mesh screen, and each core was measured for exact sediment height (L). To remove air from pore spaces, cores were saturated from the bottom-up by slow immersion in standing tap water. No air bubbles were observed along the sides of the core. While being timed with a stopwatch (t), 250 or 100 ml of tap water (V) (depending on permeability) was poured from a graduated cylinder into the core so that a constant water level above the sediment surface was maintained. Permeability in meters day^{-1} was calculated as:

$$K = \frac{VL}{Ath} \tag{1}$$

where A represents the surface area of the core and h is the height of the constant water level from the bottom of the sediment. Permeability of each core was also measured using three replicates of the "falling-head" methodology. Since the results of the two methods were highly correlated ($r^2 = 0.9954$, $p < 0.001$) only the "constant-head" results are presented here.

The porosity, or fraction of pore space in sediments, was measured in 5 cm core sections by saturating, weighing, completely drying and re-weighing each section. A known volume of sediment was saturated by spooning it into open-ended 50 ml syringes (V_{total}) filled with tap water. Syringes full of sediment were then emptied into Petri dishes and weighed (M_{wet}). The dishes were then placed in a drying oven at approximately 70 °C overnight. Dishes were weighed every 24 h until two consecutive weights changed by less than 0.1% (M_{dry}). The porosity of each core section was calculated as: $(M_{wet} - M_{dry})\rho/V_{total}$. The difference in weight represents the total loss of water from pore spaces in the sediment. The density of water (ρ) was 1000 kg m^{-3}, since salts were removed by flushing sediments with tap water.

Plastics fragments were floated from the sediments using a high-density salt solution (1.2 g cm^{-3} NaCl). Floating natural debris, such as sticks or seeds, was separated from the plastic by hand. Plastic and natural fractions of each core section were rinsed with fresh water and dried again in the oven at 70 °C. To measure grain-size distribution by weight, each fraction was sieved using five, brass standard US testing sieves of 4 mm, 2 mm, 1 mm, 0.5 mm, and 0.25 mm mesh sizes. Sieves were shaken for 15 min on a Humboldt Manufacturing Company sieve shaker to ensure separation, and each size class weighed. Mean grain sizes of each 5 cm core section were calculated using the United States Geological Survey's Grain Size Statistics Program (Poppe et al., 2004).

Up to three plastic fragments from each core, depth section, and fragment size class (total $n = 248$) were randomly selected and analyzed for composition using a Thermo Nicolet Nexus 670 model Fourier Transform Infrared Spectrometer (FT-IR). Spectra measuring background absorbance were subtracted from the sample spectra, and the results were matched to the closest reference spectrum in the machine's Thermo Omnic software.

Because the grain size distributions of the natural sediment from the impacted and control beaches were significantly different upon analysis (see Section 3 and Table 1), and small amounts of plastic were encountered in the "control" beach sediments, we constructed artificial cores to eliminate the effect of varying grain size on the response variables. Artificial cores of 20 cm height were constructed in the original 5-cm diameter clear PVC tubes, using 600 g of Kamilo Beach sediment and plastic fragments. The cores had the mean grain size distribution for Kamilo Beach throughout, and included varying concentrations of plastic fragments. Three replicate cores were constructed for each treatment level: control (0% plastic by weight), Kamilo mean (1.5%), maximum observed at Kamilo (15.9%), approximately half of this maximum (7.3%), and nearly double this maximum (29.4%). The vertical distribution of plastic in the artificial cores also mimicked the beach cores, with about 50% of the fragments in the top 5 cm, and 95% in the top 15 cm (see Section 3). Plastic fragments were added with the same

Table 1
Porosity, percent plastic by weight, and grain-size distributions of beach sediment cores taken from Kamilo and Waikapuna beaches on the island of Hawai'i. The grain size of the plastic fragments encountered (mainly on Kamilo Beach) is shown in the lowest row.

Beach	Depth (cm)	Mean porosity	Mean % plastic	Grain size distribution (percent, mm categories)					
				<0.25	0.25–0.5	0.5–1	1–2	2–4	>4
Kamilo (impacted)	0–5	0.273	3.31	0.9	12.3	26.6	22.4	16.5	21.2
	5–10	0.281	1.79	1.4	13.5	30.8	23.2	16.1	15.0
	10–15	0.287	0.61	1.9	14.1	32.4	24.9	13.5	13.2
	15–20	0.291	0.30	2.0	13.4	32.6	24.8	12.3	14.8
	20–25	0.284	0.02	1.6	16.6	40.5	23.7	8.0	9.6
Mean		0.283	1.34	1.5	14.3	32.7	24.4	14.0	13.1
Waikapuna (control)	0–5	0.271	0.12	23.3	38.6	21.6	9.6	3.7	3.2
	5–10	0.263	0.02	20.9	33.6	20.6	13.0	5.2	6.6
	10–15	0.276	0.02	22.2	35.2	20.0	12.5	6.4	3.6
	15–20	0.286	0.01	22.5	36.7	20.3	13.1	5.8	1.5
	20–25	0.279	0.00	31.8	41.8	11.4	7.2	4.2	3.6
Mean		0.274	0.03	23.8	36.9	19.2	11.3	5.1	3.8
Plastic fragments only				0.2	1.6	8.7	11.7	33.3	44.5

mean size distribution as observed in the beach cores (note that the mean grain size of plastic fragments is greater than that of the natural sediments, Table 1). The cores were then subjected to "constant-head" permeability measurements as above.

To measure the thermal diffusivity and heat capacity, the completely dry artificial sediment cores were placed in Styrofoam cylinders with temperature data loggers at the bottom and were set beneath heat lamps for 4 h. A temperature data logger away from the heat lamp was used to track variation in laboratory background temperature during trials. Given sufficient time, the difference between ambient temperature and that of sediments will reach equilibrium (T_∞), based on the diffusion of heat:

$$\frac{dT}{dt} = \alpha \frac{dT}{dz} \tag{2}$$

where T is temperature, t is time, α is thermal diffusivity and z is distance. The transient solution to Eq. (2) is (De Vries, 1963):

$$T = T_\infty \, erfc\left(\frac{z}{2\sqrt{\alpha t}}\right) \tag{3}$$

Eq. (3) was fit to the mean difference between ambient temperature and that of the sediments as a function of time. T_∞ and α were varied to find the best fit to the data, and the standard error was computed from the three trials. For sediments, α is composed of a sediment and air component. However, changes in α result from changes in the sediment properties, since the fraction of air in cores (i.e. porosity) did not change significantly (see Section 3). The equilibrium temperature difference (T_∞) is inversely proportional to the heat capacity of the sediments (Bristow et al., 2001).

3. Results

The top 5 cm of Kamilo Beach averaged 3.3% plastic by weight, with a maximum observed value of 30.2%. Presenting concentrations by weight is convenient, but because of the difference in density between plastic (<1.2 g cm^{-3}) and natural sediments (about 2.6 g cm^{-3}), these metrics underestimate the volume of plastic in the beach by more than a factor of two. Although plastic fragments were encountered in the deepest sections (20–25 cm), over half of the total plastic was located in the top 5 cm, and nearly 95% was found in the top 15 cm (Table 1). Parallel to the shoreline, the abundance of plastic fragments was patchy and occurred in substantial concentrations in all three vertical beach zones at Kamilo. Waikapuna Beach, the "control" site, had an average of 0.1% plastic in its top 5 cm, with a maximum observed value of 0.8%. Of 248 plastic fragments and pellets analyzed using FT-IR, 85% were polyethylene, 14% were polypropylene, and 1% were polystyrene or polyurethane.

Permeability of Kamilo Beach cores (mean 123 ± 83 m d^{-1}) was significantly higher than Waikapuna cores (40 ± 20 m d^{-1}) (t-test, $p < 0.0001$). We were unable to attribute the permeability to a difference in plastic concentrations alone. The permeability difference was most likely related to a significantly coarser-grained natural sediment at Kamilo (mean 1.200 ± 0.33 mm) than at Waikapuna (mean 0.467 ± 0.33 mm) (two-sample Kolmogorov–Smirnov test on the distributions, $p < 0.0001$). The grain size of the deepest sections, which were least impacted with plastics, was also different. Grain size did not impact the porosity of sediments, which did not significantly differ between beaches or depths (Table 1).

Artificially-constructed cores that mimicked the mean grain-size distribution of Kamilo Beach, but contained varying percentages of plastic, demonstrated that these fragments change the permeability and heat transfer properties of sediments. Permeability in control cores (0% plastic) averaged 152 ± 9 m d^{-1}, and increased with increasing plastic composition up to 294 ± 52 m d^{-1} (Fig. 2), significantly so in the two treatments with the highest plastic load (ANOVA, $p = 0.002$).

We did not specifically test the mechanism for the increase in permeability due to the addition of plastic. However, the permeability of entire sediment cores is controlled by the section with the minimum permeability, which in this case was usually the lowest section. The addition of plastic fragments from the 0% to 29% artificial cores increased the minimum mean grain size by 0.142 mm. Since the minimum mean grain size of our field cores from both beaches was significantly related to the permeability of those cores (Fig. 3), we can estimate the change in permeability due to the grain size effect in the artificial cores. Using the slope of the regression line ($r^2 = 0.522$, $p < 0.001$) this increase in minimum mean grain size predicts a permeability increase of 28.6 m d^{-1}. Instead we observed an average increase between the lowest and highest plastic treatments of 142.2 m d^{-1} (Fig. 2). This discrepancy reflects variability in the relationship between grain size and permeability in our natural cores, but is also evidence that changes in permeability from the addition of plastic are probably due to other factors than simply due to the increased size of the fragments.

Increasing plastic in the cores also insulated the subsurface environment against increasing temperatures. Sediments with plastics warmed more slowly, with as much as a 16% decrease in

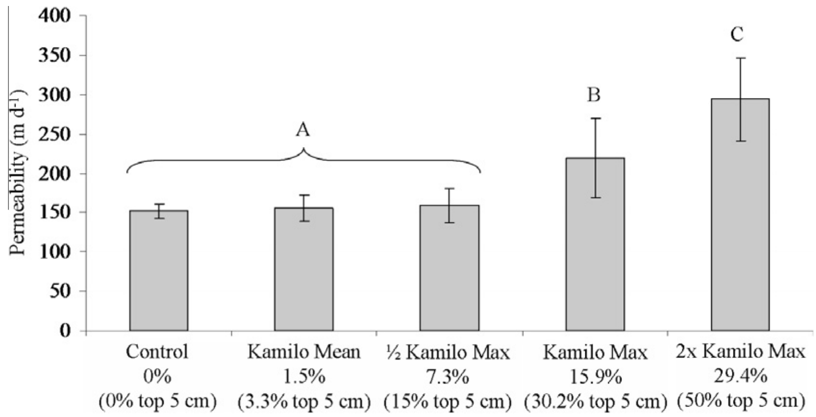

Fig. 2. "Constant-head" permeability of artificially constructed sediment cores with standardized grain-size distribution and varying plastic fragment composition (by weight). All core construction materials were taken from Kamilo Beach, HI, and grain-size and plastic fragment distribution with depth were set to mimic mean Kamilo Beach conditions. Three replicate cores were constructed for each treatment. Significant differences among treatments from the ANOVA ($p = 0.002$) and post hoc LSD test are listed in capital letters.

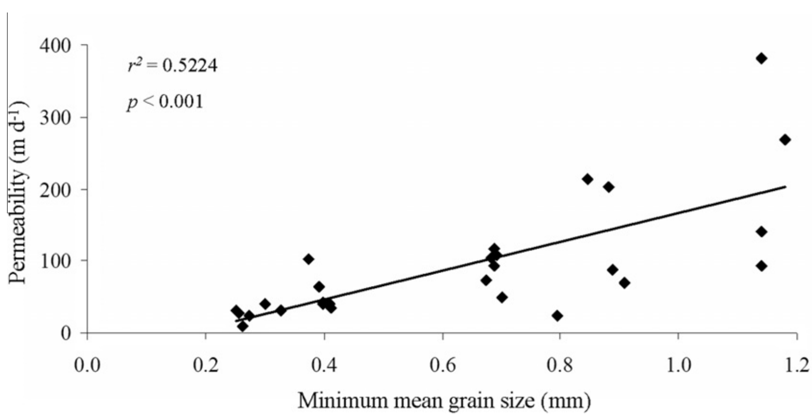

Fig. 3. Relationship between the permeability of cores taken from Kamilo and Waikapuna beaches and the mean grain size of the 5 cm section in that core with the lowest mean grain size.

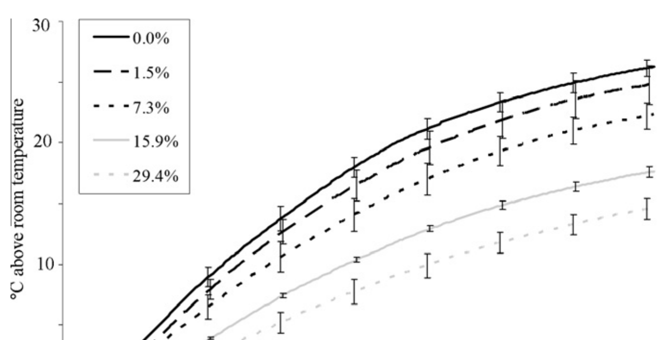

Fig. 4. Insulating properties of plastic in artificially constructed sediment cores with standardized grain-size distribution and varying plastic fragment composition (by weight). All core construction materials were taken from Kamilo Beach, HI, and grain-size and plastic fragment distribution with depth were set to mimic mean Kamilo Beach conditions. Three replicate cores were constructed for each treatment. Treatment levels are described in Fig. 2. Cores were placed in Styrofoam cylinders with temperature loggers at the bottom and heated with a heat lamp for four hours. Temperatures within the cores were standardized by a separate logger to account for variations in the laboratory temperature during trials.

thermal diffusivity. Maximum temperatures at the base of the cores, which are inversely proportional to the heat capacity of surficial sediments, decreased by as much as 21% (Fig 4). This is consistent with lower thermal conductivities and higher heat capacities for plastics than for sediments (De Vries, 1963; Rosato et al., 2004).

4. Discussion

As small plastic pellets and fragments accumulate on the world's beaches, beach organisms may experience increased desiccation underneath patchily-distributed plastic loads due to increased permeability of the sediments there. Our study was unable to isolate the specific mechanism for this increased permeability, but it is most likely a combination of reduced friction from smooth plastic surfaces and an increase in the overall grain size due to more resistant, larger plastic fragments.

Increased grain size, permeability, and desiccation stress of plastic beaches could affect a variety of taxa and their eggs, including crustaceans (e.g. Penn and Brockmann, 1994), mollusks (e.g. D'avila and Bessa, 2005), polychaetes (e.g. Di Domenico et al., 2009), fish (e.g. Quinn, 1999), and various interstitial meiofauna (e.g. Albuquerque et al., 2007). Meiofauna communities may be especially vulnerable to these effects because their diversity may be the highest in the midshore region (Armonies and Reise, 2000), where plastic particles first accumulate in wrack lines. Although small increases in plastic concentration increased permeability, only the highest treatments showed statistically significant changes, equivalent to higher concentrations of plastic on a heavily-impacted beach. However, as plastic production continues to increase worldwide, beaches with high plastic loads such as Kamilo may unfortunately become the beaches of the future.

Changing the permeability of beach sediments may alter biogeochemical and trace element cycling in beach sediments. Increasing the permeability of beach sediments allows greater volumes of water to be flushed through the beach (McLachlan, 1982). Water flowing into the beach carries oxygen and organic matter that are consumed by organisms living in interstitial spaces (Jiao and Li, 2004). Greater fluxes of organic matter may allow for larger populations of interstitial organisms. This biological activity enriches beach water with nutrients and metabolites (Hays and Ullman, 2007; Santos et al., 2009). Changes to the flux of water through the beach may also alter the rate that nutrients are returned to the coastal ocean. The metabolic activity of organisms generates horizontal and vertical gradients of oxygen and redox conditions (McLachlan, 1989; McLachlan and Dorvlo, 2005). The location and movement of redox gradients will impact the cycling of redox sensitive elements within beaches, including iron, manganese and uranium (Charette and Sholkovitz, 2006).

It is possible that the thermal insulation properties of plastic fragments will reduce evaporation, balancing some of the effects of increased permeability. Reduced subsurface temperatures could also have a variety of effects on beach organisms, including those with temperature-dependent sex-determination such as sea turtles (Yntema and Mrosovsky, 1982). Buried eggs underneath high plastic fragment loads have the potential to need longer incubation periods, and hatch lower numbers of females due to this insulating effect. Even a low concentration of plastic (1.5%) in the artificial sediment cores lowered thermal diffusivity by 2.5% and decreased the maximum temperature by 0.75 °C. These relatively modest changes are relevant to the window of sex-determination temperatures in sea turtles. For instance, the incubation temperature difference between hatching 100% males or 100% females in loggerhead sea turtles (*Caretta caretta*) is only 4 °C (Yntema and Mrosovsky, 1982). Hawksbill turtles (*Eretmochelys imbricata*) in Antigua experienced the same shift from 100% males to 100% females over only a 1.8 °C window (Mrosovsky et al., 1992).

Beyond the already established effects of ingestion, chemical leaching, and pollutant adsorption, plastic pellets and fragments may change the physical properties of beaches that they contaminate by increasing permeability and lowering subsurface temperatures. Future research will examine the responses of specific beach organisms to the physical effects of increasing concentrations of plastic sediments. Although extremely labor-intensive, removal of plastic pellets and fragments during beach clean-ups could alleviate these physical effects. Ultimately, the only long-term solution to the various effects of plastic fragments would be to stop their introduction into marine environments in the first place.

Disclosure statements

All four authors of this manuscript have no past, current or potential conflicts of interest relating to this work.

This work and associated data have not been published elsewhere and are not in consideration for publication elsewhere. They were presented at the 5th International Marine Debris Conference in March of this year, and the abstract may be included in subsequent conference proceedings.

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Role of authors

Henry Carson designed the study, carried out field and laboratory experiments, coordinated the analysis of samples, performed statistical analysis, and drafted the manuscript.

Steven Colbert helped design the study, assisted in laboratory work, performed statistical analyses, and drafted portions of the manuscript.

Matthew Kaylor helped design the study, assisted in all field and laboratory work, performed the FT-IR analysis of plastic, and edited the manuscript.

Karla McDermid secured funding for the research, developed the original research question, helped design the study, and edited the manuscript.

All authors have approved the final submission.

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